UNCLASSIFIED

AD NUMBER

AD874249

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution limited to U.S. Gov't. agencies and their Contractors; Specific authority; 8 June 1971. Other requests must be referred to Naval Research Laboratory, Attn: Code 8200. Orlando, FL 32806.

AUTHORITY

NRL ltr, 26 Nov 2003

THIS PAGE IS UNCLASSIFIED

AD874249

AD No. ____
DDC FILE COPY

NRL Memorandum Report 2146

Underwater Sound Absorbers: A Review of Published Research with an Annotated Bibliography

J. L. Lastinger and G. A. Sabin
Methods and Systems Branch
Underwater Sound Reference Division

August 5, 1970

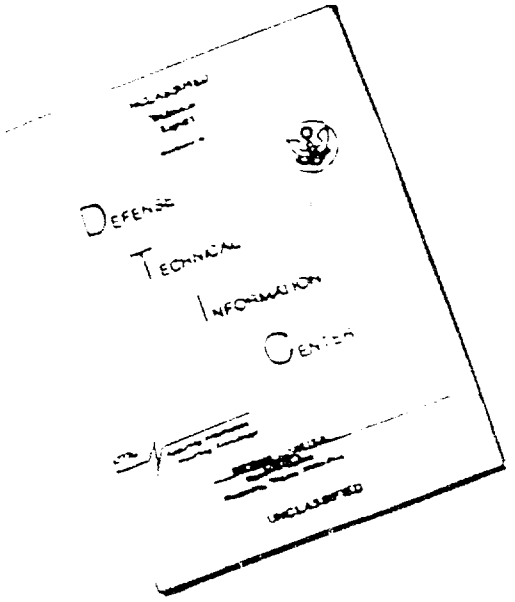
DDC
RECEIVED
SEP 14 1970
C

NAVAL RESEARCH LABORATORY
Underwater Sound Reference Division
P. O. Box 8337, Orlando, Florida 32806

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Director (Code 8200), Naval Research Laboratory, P. O. Box 8337, Orlando, Florida 32806.

38

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

Contents

Abstract ii
Problem Status ii
Problem Authorization ii

Introduction 1

Analysis of Media 1

Hooke's Law 1

Wave Propagation 2

Reflection and Impedance 4

Porous Materials 5

Nonrigid Porous Materials 5

Elastic and Rigid Porous Materials 6

Resonant Absorbers 7

Broadband Absorbers 9

Pressure Absorbers 9

Velocity Absorbers 9

Test Methods and Facilities 10

The Pulse Tube 11

The Standing-Wave Tube 11

The Reverberation Chamber 12

Panels in Free Field 12

Conclusion 13

Annotated Bibliography 15

Unclassified Literature 15

Classified Literature 33

Abstract

The theoretical behavior of acoustic media is reviewed briefly to obtain an insight into the nature of the absorption problem and the limitations imposed by the theory. Then, the status of resonant and broadband absorbers and the methods used to evaluate them are examined. In conclusion, several areas needing further investigation are specified. It is pointed out that the need for absorbers within a tank would be reduced significantly--perhaps eliminated--if the acoustic impedance of the tank wall could be made approximately equal to that of water. An annotated bibliography is included.

Problem Status

This is an interim report on the problem.

Problem Authorization

NRL Problem S02-30

Project RF 05-111-401-4471

Manuscript submitted February 27, 1970.

UNDERWATER SOUND ABSORBERS

Introduction

The literature on underwater sound absorbers and absorption has been reviewed with the intention of summarizing what has been done and of specifying those areas in need of further research.

Most of the classical theory of air acoustics applies equally well to other media; hence, in the next section, the general principles related to the propagation of sound in a homogeneous medium such as air or water will be examined to arrive at some idea of the characteristics of an ideal absorber. In succeeding sections, the development and present status of resonant and broadband absorbers and the methods used to evaluate them will be discussed. It should be possible then, to ider .ify problem areas and suggest some approaches to the solution of the problems.

The bibliography accompanying this report is not intended to be exhaustive, but to provide the reader with a survey of the major work that has been accomplished, as well as some background material.

Analysis of Media

Hooke's Law

The theory of linear elasticity states that the stresses in a medium are linear functions of the strains. Mathematically,

$$\sigma_i = c_{ij}\varepsilon_j \quad (i,j = 1, 2, \ldots 6),$$

where σ_i are the stresses, ε_j are the strains, and c_{ij} are the 36 elastic constants (reference 4, p. 99 and reference 24, p. 60). The requirement that the elastic energy be a single-valued function of the strain reduces the number of independent constants to 21 for the most general case. When the medium is isotropic, the number reduces to 2, usually denoted λ and μ, and known as Lamé's constants. The constant μ is the shear modulus (rigidity), but λ does not correspond to any commonly measured elastic constant. It is related to Young's modulus (E) and to the bulk modulus (K) by the equations (reference 17, pp. 9-10)

$$E = \frac{\mu(3\lambda + 2\mu)}{\lambda + u}$$

$$K = \lambda + 2\mu/3.$$

Thus, only if $\mu = 0$ (fluid) does λ correspond to the bulk modulus.

Wave Propagation

Kolsky (reference 17) analyzes wave propagation both in elastic and lossy media. In general, his treatment will be followed. Because we are concerned only with harmonic solutions, we assume an expression of the form

$$u = u_0 e^{j(\omega t - kx)} \tag{1}$$

as a positive-traveling solution (reference 17, p. 13) to the plane-wave equation

$$\rho \frac{\partial^2 u}{\partial t^2} = (\lambda + 2\mu) \frac{\partial^2 u}{\partial x^2} \tag{2}$$

and substitute Eq. 1 into Eq. 2. Here, u is the particle displacement in the x direction, u_0 is the displacement amplitude, j is $\sqrt{-1}$, ω is angular frequency, t is time, $k = \omega/c$ is the wave number, and c is the phase velocity of the traveling wave. The resulting equation requires that $c^2 = (\lambda + 2\mu)/\rho$, which is predictable from the form of Eq. 2. But what happens when there are losses in the medium?

A lossy medium implies that the linear relation $\sigma_i = c_{ij}\varepsilon_j$ does not hold between stresses and strains. Thus, before the wave equation for a lossy medium can be derived, the relation between σ_i and ε_j must be found. From experiment, it has been observed that $\sigma_i = c_{ij}\varepsilon_j + c_{ij}'(\partial\varepsilon_j/\partial t)$, where c_{ij}' are constants, is approximately true for many real, lossy solids; this is the relation assumed here (reference 17, p. 116). The reader should remember, however, that the resulting wave equation and all that may be derived from it depend upon the stress-strain relation just postulated.

Following the same general procedure as for the perfectly elastic medium, we arrive at the wave equation

$$\rho \frac{\partial^2 u}{\partial t^2} = (\lambda + 2\mu) \frac{\partial^2 u}{\partial x^2} + (\lambda' + 2\mu') \frac{\partial^3 u}{\partial x^2 \partial t}. \tag{3}$$

Here, λ' and μ' are the c_{ij}' for an isotropic, lossy, medium; they are not the imaginary parts of a complex $\bar{\lambda}$ and $\bar{\mu}$. For instance, from the

paragraph above, it is apparent that the stress-strain equation for shear motion in a lossy medium is $\sigma = \mu\varepsilon + \mu'(\partial\varepsilon/\partial t)$. If we assume a harmonic solution of the form $\sigma = \bar{\mu}\varepsilon = \bar{\mu}\varepsilon_0 e^{j\omega t}$, allowing the elastic constant $\bar{\mu}$ to be complex, and substitute into the stress-strain equation, then

$$\bar{\mu}\varepsilon_0 e^{j\omega t} = \mu\varepsilon_0 e^{j\omega t} + \mu' j\omega\varepsilon_0 e^{j\omega t},$$

and

$$\bar{\mu} = \mu + j\omega\mu'.$$

Again, using a harmonic solution for Eq. 3 of the form

$$u = u_0 e^{j(\omega t - kx)},$$

we find that the following relation must hold:

$$\rho\omega^2 = (\lambda + 2\mu)k^2 + j(\lambda' + 2\mu')k^2\omega. \qquad (4)$$

So, k must be complex; and we set $k = k_1 + j\alpha$. (The usual convention in physics--which is what Kolsky follows--is to write a harmonic solution to the wave equation in the form $e^{j(\omega t - kx)}$. Then, when k is complex, it must be written as, say, $k_1 + j\alpha$, if k_1 is to be the wave number and α the attenuation constant. On the other hand, electrical engineering practice favors the form $e^{j\omega t - \gamma x} = e^{j\omega t - (\alpha + jk)x}$, so that the propagation constant is $\alpha + jk$. After this section, the engineering practice will be followed exclusively.) Solving for k_1 and α, we obtain:

$$k_1 = \omega\left\{\frac{(\lambda + 2\mu)\rho}{2[(\lambda + 2\mu)^2 + (\lambda' + 2\mu')^2\omega^2]}\left[\left(1 + \frac{[(\lambda' + 2\mu')\omega]^2}{(\lambda + 2\mu)^2}\right)^{1/2} + 1\right]\right\}^{1/2} \qquad (5)$$

and

$$\alpha = \omega\left\{\frac{(\lambda + 2\mu)\rho}{2[(\lambda + 2\mu)^2 + (\lambda' + 2\mu')^2\omega^2]}\left[\left(1 + \frac{[(\lambda' + 2\mu')\omega]^2}{(\lambda + 2\mu)^2}\right)^{1/2} - 1\right]\right\}^{1/2} \qquad (6)$$

as the relations between the propagation constant, $k_1 + j\alpha$, and the material constants λ, λ', μ, μ' (reference 17, p. 117).

Because of the need to distinguish between the complex propagation constant and the complex velocity, we will go back to Eq. 4 and re-examine it. It is at this equation that one of three possible paths was chosen. It was stated that k must be complex, and we chose the real and imaginary parts to be k_1 and α, respectively. When the term $k_1 + j\alpha$ is substituted into the assumed solution, it will be seen that k_1 corresponds to the usual real wave number ω/c, and α to the attenuation per unit distance. We could have chosen c to be complex, however. Then, $k = \omega/c = \omega/(c' + jc'')$. Or, we could have let $k = \omega/c = (\omega' + j\omega'')/c$.

In either of these cases, the relations between c and λ, λ', μ, μ' and between ω and λ, λ', μ, μ' would be different. As with the complex k, however, the imaginary portion of the complex number would represent attenuation of the wave.

Reflection and Impedance

The relation between the complex pressure reflection coefficient at normal incidence and the impedances of two homogeneous media at their plane interface is expressed by the well-known equation (reference 9, p. 2)

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \tag{7}$$

where R is the reflection coefficient for a wave in medium 1, Z_2 is the specific acoustic impedance at the interface, and Z_1 is the characteristic impedance of medium 1. When medium 2 is not infinite, there will be a reflection from its second plane boundary; the impedance Z_2 at its first boundary will be (reference 9, p. 3)

$$Z_2 = Z_0 \frac{Z_3 \cosh \gamma\ell + Z_0 \sinh \gamma\ell}{Z_3 \sinh \gamma\ell + Z_0 \cosh \gamma\ell}, \tag{8}$$

where Z_0 is the wave, or characteristic impedance of medium 2, Z_3 is the impedance at the second boundary of medium 2, γ is the propagation constant ($\alpha + jk$), and ℓ is the thickness of medium 2. These two equations are used in the analysis of measurements on material samples in impedance tubes.

Strictly speaking, Eq. 7 was derived for two homogeneous media; in practice, it can be applied also in the case of reflection from a composite medium, provided that the impedance is defined as the effective, or averaged impedance over a surface that is large in comparison with the inhomogeneities, and provided further that the reflection is measured sufficiently distant from the interface.

Equation 8 can be used also for composite (porous) media, if it be understood that c and α are "effective" sound speed and attenuation constants. The subject of porous media will be examined in more detail in the next section.

From Eq. 7, it is obvious that the condition for zero reflection is $Z_1 = Z_2$. If medium 1 is water and medium 2 is the absorber, then the impedance of the absorber must be real and equal to the ρc of water. But Eq. 8 involves, in general, complex impedances and propagation constants. Indeed, γ must be complex, or there would be no attenuation at all in medium 2. A plot of Eq. 8 in the complex impedance plane, with thickness ℓ as the independent parameter, is similar to a logarithmic spiral. With proper control of the material parameters, and for small values of ℓ, it will pass very close to the value of ρc on its first loop. Such an

absorber is called a resonant absorber, because it is useful only in a narrow frequency band. A detailed analysis of this type of absorber is given in reference 18.

For broadband absorbers, it is necessary to use a material whose characteristic impedance, Z_0, approaches that of water, but whose attenuation constant is, nevertheless, large enough to be useful. In the Appendix to reference 18, it is shown that for best impedance match, the magnitude of the characteristic impedance should be equal to the ρc of water. Moreover, the attenuation constant cannot be too large, if the reflection at the interface is to be kept low. Using Eqs. 2 and 6 of reference 18, one can calculate that the quantity $\alpha c/\omega$ must be less than 0.2, even when $|Z_0|$ equals the ρc of water, if the pressure of the interface reflection is to be at least 20 dB below that of the incident wave. In practice, meeting the last requirement presents no difficulty, but meeting the first one does. By using a gradual impedance-transition zone, however, the effect of the interface can be minimized. This method will be discussed later, under "Broadband Absorbers."

Porous Materials

For the purpose of discussion, porous materials can be divided into two classes: (1) nonrigid porous materials consisting of particulate matter such as sand or clay, in which there is little or no rigidity between particles; and (2) porous materials having considerable rigidity, such as concrete or fiber metal.

Nonrigid Porous Materials

Consider a two-phase mixture of solid particles whose diameters are small in comparison with the wavelength, randomly dispersed in an oscillating, viscous, liquid medium. If we hold the percentage of solid matter constant and allow the particle diameter to vary, then the total viscous force on all the particles will increase as the diameter decreases, provided that the particles remain motionless. The particles will not remain motionless, however, but will move faster with decreasing size. There are, then, two opposing actions: one increases viscous losses as particle diameter decreases, and the other reduces viscous losses because of the decreasing relative velocity between solid and liquid. Because of this, there will be an optimal particle diameter corresponding to maximum attenuation for a given mixture at a given frequency.

In reference 6, Urick derived expressions for the attenuation as a function of particle diameter, concentration, density, and frequency, and performed experiments to test the predictions. He examined the viscous absorption in aqueous suspensions in the frequency range 1 to 15 MHz, using sand and kaolin particles whose diameters were in the 1- to 10-micron range. For low particle concentrations (less than 10%), the absorption was a linear function of the concentration, as predicted. The theoretical relation between absorption and particle diameter also was verified. Numerous investigations of the absorption in suspensions and mixtures

have been made since, at lower frequencies, but theory shows that for large absorption at low frequency, it is necessary to use heavy particles that will not partake of the motion of the water. Meyer and Tamm (reference 14) tested lead dust in oil and achieved useful absorption; because the suspension could be maintained only by continual stirring, it was decided that this was not a practical approach.

Elastic and Rigid Porous Materials

The empirical theory of sound propagation in viscous-fluid-saturated, elastic, and rigid porous media has been derived in considerable detail in references 5, 9, 25, 26, 35, 37, 38, and 52. The earlier work of Beranek and Zwikker deals with air acoustics, but the theory is applicable to liquid-saturated media as well, if the assumptions (such as rigidity) can be satisfied. Zwikker analyzed propagation both in rigid and elastic porous media, but did not consider shear rigidity in the latter. Biot examined elastic porous media from the theoretical viewpoint, however, and included shear rigidity in his analysis.

Assume that a viscous-fluid-saturated, porous medium can be described by saying that the solid portion of the medium is an elastic material such that the dry frame possesses both compressive and shear elastic moduli, and that all elastic and flow properties of the medium are independent of direction. Upon these assumptions, Biot (references 25 and 26) derived the wave properties of the medium. He found that there are two dilational wave modes and one shear wave mode in the medium, each possessing its own propagation constant. The constants are complicated functions of the medium's elastic and flow properties. Of the two dilational waves, the slower one has much greater attenuation than does the faster one--as much as an order of magnitude greater, at low frequencies. Hence, under some conditions, the lower-velocity wave may not be observed.

In reference 38, Biot generalizes the theory to include anisotropy, viscoelasticity, interfacial phenomena, and non-Newtonian flow, and introduces the concept of the viscodynamic operator. In connection with the generalized theory, the reader may want to read Savins' account (reference 55) of various flow peculiarities that can affect wave propagation in porous materials. In general, when the dimensions of the cavities approach the thickness of the interfacial layer, the interface properties of the liquid, rather than the bulk properties, may become dominant. For instance, pore blockage, resulting in reduced permeability of the material, may occur because of molecular adsorption on the pore walls. Biot's phenomenological approach is applicable, however, regardless of the hidden mechanisms involved.

When the impedance tube is used to analyze porous media, the data should be interpreted cautiously. Because there may be more than one wave mode in an elastic porous medium, there is a possibility of more than one propagation constant for the medium. Nevertheless, we speak of a particular sound speed and attenuation constant for a porous medium because it is convenient. But when we do, it must be kept in mind that

these are effective values that apply to the resultant when the wave modes are combined.

So far, there seems to have been almost no attempt to correlate the measured data for porous underwater sound absorbers with the theory for porous materials. This may be due, in part, to the fact that several dynamic parameters, such as effective density and flow resistance for the fluids, must be measured before the theory can be applied; moreover, measurement of these quantities requires equipment that is not a usual part of laboratories concerned with underwater sound measurements or research. The amount of research that has been conducted on porous materials as absorbers has been very limited. Some of this will be referenced in "Broadband Absorbers."

Resonant Absorbers

Before World War II, it had been observed that clouds of bubbles in water would attenuate a sound wave. To apply this idea to the acoustic camouflage of ships and submarines during the war was a natural step. Attempts were made actually to discharge bubbles into the water around the vessel; this idea proved infeasible, because the bubble distribution could not be controlled adequately, particularly when the ship was under way (reference 28). This observation led to the concept of fixing the distribution of bubbles by imbedding them in a layer of viscoelastic material such as rubber. (The losses originate in the shear mode vibration, which is activated when the bubbles oscillate.) Since then, three types of resonant absorbers that operate on this principle have been developed, and the concept of the viscous fluid-flow absorber has emerged. The four types will be discussed.

1. A resonant absorber containing geometrically precise and ordered cavities was developed by the Germans during World War II, and was called Alberich (reference 12). This material was constructed by making holes in one rubber mat and attaching a second solid rubber mat to one side of the first. The other side of the holes was closed by the hull of the vessel to which the rubber structure was attached. The acoustic behavior of this absorber is analyzed by considering it as a lumped-element mechanical network. The original theory (reference 12) does not provide any direct relationship between the theoretical parameters and the physical properties of the rubber. An improved theory with supporting experimental data has been proposed by Meeks (reference 42).

The resonant absorber can furnish an absorption bandwidth of about one octave, measured between the 20-dB-down frequency points. The effectiveness is greatly diminished by a shift in either temperature or pressure. The absorption characteristics of the resonant absorber are limited by the dynamic properties (loss factor and elastic modulus) of the rubber; apparently, further development must come mostly through materials improvement. Because loss of absorption with increase in hydrostatic pressure probably is due largely to collapse of the cavity structure in the rubber,

one could expect an improvement if the integrity of the structure is maintained by applying air pressure to these cavities. The results of such tests are reported in reference 57.

2. Another approach was used during the war years by the research group at Massachusetts Institute of Technology. By mixing randomly distributed air bubbles with rubber, it is possible to produce a medium whose sound speed and attenuation are such that a thin layer will behave as an absorber over a relatively narrow frequency range (about one octave). The approach here was from the viewpoint of a thin-layered medium, rather than a mechanical circuit. Thus, the impedance--hence, echo reduction--is directly related to the properties of the material through the transmission line equation (Eq. 8). Because the layer thickness, ℓ, is small in comparison with the wavelength, Eq. 8 can be simplified. More often, the equation relating the impedance to the elastic modulus and the loss factor is used for thin layers. Reference 18 is a thorough study of the theory involved in absorption; several practical applications are worked out.

3. The metal-loaded rubber absorber is similar to the M.I.T. type, except that small particles of metal powder are added to the rubber mix. When the voids or bubbles are introduced to increase losses, the density and sound speed are decreased unavoidably. Adding metal powder helps to restore the "pc" of the rubber so that the impedance match with water still is adequate. References 18 and 21 discuss this development.

4. The fourth type is a new development from Germany, so far only experimental. It is a device that utilizes the shear viscosity of highly viscous fluids to dissipate acoustic energy through transformation of the axial velocity V_a to radial velocity V_r. See Fig. 1.

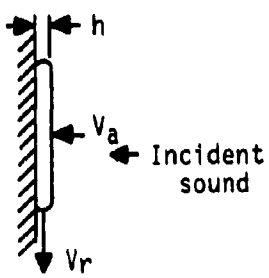


Fig. 1. Diagram showing the principle involved in the fluid velocity transformation absorber.

If the fluid thickness h is very small, then V_r will be quite large. The impedance of the device can be adjusted, therefore, by varying the fluid thickness, the fluid density, viscosity, etc. References 46, 51, and 54 discuss this absorber. Theory requires that the suspension for the diaphragm be acoustically soft, which precludes operation at hydrostatic pressure greater than a few pounds per square inch. Bandwidths of several octaves are being achieved now, however, so the device may find application.

At present, the concept is of interest largely because of the novel approach to the absorption problem. Recall that absence of reflection requires only that the impedance at the surface of the water-absorber interface equal (or approximate) that of water. It is immaterial what "black box" behind the interface actually absorbs the energy. Possibly another "device" approach might be useful over large bandwidths while permitting greater range of hydrostatic pressure and temperature. This approach seems worthy of research effort.

Broadband Absorbers

Broadband absorbers can be divided into two categories: "Pressure" absorbers that depend upon losses associated with the acoustic pressure in the material; and "velocity" absorbers that depend upon viscous losses associated with the particle velocity in the material. In general, the first type includes impervious, highly compressible, lossy materials; the second consists of porous, relatively incompressible materials.

Pressure Absorbers

The pressure absorber was studied rather extensively by the German scientists at the same time that they were developing the resonant absorber (reference 12, Chap. 4). The action of the pressure absorber depends upon the fact that viscoelastic materials have high shear loss. By adding tiny air bubbles (whose resonance frequencies are above the frequency range of the absorber) or substances such as talc, wood powder, *etc.*, the shear loss is brought into action and, at the same time, the material is rendered more compressible. The mixture is formed into pyramids, pointed fins, or cones that create, in effect, a soft-bounded, lossy channel down which the sound wave moves. The operational frequency band of the absorber depends upon the length of the cone and the spacing between cones. The broadband absorber "Fafnir," developed by the Germans, is in use today with only minor modifications.

Because the material is similar to that used in making resonant absorbers, the broadband pressure absorber also is subject to limitations on temperature and pressure. A major effect of a change in temperature, however, is a shift in the resonance frequency of the cavities in the resonant absorber; of course, this is not a severe limitation on the use of a broadband absorber.

Velocity Absorbers

By its nature, the pressure absorber cannot remain effective at high hydrostatic pressure, for it must be quite compressible to function at all. On the other hand, the water-saturated, porous, velocity absorber should be insensitive to hydrostatic pressure changes within the range encountered in the ocean, because the viscosity of water changes less than 8% in this range; but temperature affects the viscosity of water considerably, causing it to decrease by 50% from 0 to 30°C (reference 10, p. 346). In the low-frequency limit, the theoretical attenuation constant

for a rigid, porous material varies as the square root of the viscosity. At higher frequencies, the dependence is even less. The effect of temperature on the attenuation, therefore, should not be large.

Darner (reference 19) reports that the absorption coefficient of the porous absorber Insulkrete does not change at pressure up to 1000 psi or temperature down to 3°C, starting from room ambient values. Reference 56 reports little change in the attenuation constant of water-saturated wood up to 10 000 psi. Apparently, pressure-temperature data on water-saturated porous absorbers other than these are not available.

Meyer and his coworkers tested metal wool and glass wool, but concluded that the attenuation was too small to be useful practically. Neither type of wool, however, was a rigid or even a semirigid material. Each consisted of fibers that were free to move with the liquid; hence, it had to be analyzed as a suspension. New materials available today, such as fiber metals and sintered, porous metals should absorb better, because they possess some rigidity. Theory predicts an optimum size for particles of a suspension when the particles are free to move; for perfectly rigid fibrous frameworks, the smaller the fiber, the more the attenuation. Thus, the role of materials research is, again, a key factor in progress.

Applying absorbing material to the lining of a test tank requires careful consideration of all the specifications the tank must meet: the frequency, temperature, and pressure ranges over which the tank will operate; the volume that can be allotted to the absorber; and the acceptable level of reflection from walls--all will have to be considered in selecting the best material. Cramer examines this problem in reference 40.

In applying a broadband absorber material whose acoustic characteristics do not match those of water, it is important that a gradual change of impedance from one medium to the other take place to minimize reflection at the boundary. Usually, this is accomplished by using wedge-shaped blocks of the absorber. The dramatic decrease in reflection that can be obtained by tapering the ends of the absorber is well illustrated by Fig. 1 of reference 40. The effect of gradual transitions has been examined theoretically by Schoch in reference 11, and by Miller in reference 29. The theoretical treatment is difficult and the optimal transition rate is not known, but it is found in practice that a transition zone of one-third to one-half wavelength at the lowest operating frequency should be used.

It seems doubtful that knowledge of the optimal transition law would lead to much improvement in present broadband absorbers, because the ultimate limit is the attenuation in the material itself.

Test Methods and Facilities

Many methods have been used to measure sound absorbing materials; basically, all of them consist in setting up a known (measurable) acoustic

field and measuring the effect of the absorber upon this field. To keep the mathematics and the data reduction process from becoming too complicated, the geometrical configuration of the field is made as simple as possible, which also reduces the number of parameters that can operate to decrease the accuracy.

Four basic techniques that have been used to evaluate underwater sound absorbers are: (1) the pulse tube, (2) the standing-wave tube, (3) the reverberation chamber, and (4) measurements on panels under free-field conditions.

The Pulse Tube

In principle, the pulse tube consists of a water-filled, rigid-wall, one-dimensional waveguide with a transducer at one end and the sample to be measured at the other. The electronic system furnishes a pulsed sinusoidal signal to the transducer, which transmits the acoustic signal and may act also as the receiver of the reflected signal. If the transducer is not used as the receiver, then a probe hydrophone is mounted somewhere along the tube to perform this function. Often, provision is made to measure both the magnitude and the phase of the reflected signal. If the sample is terminated by a known impedance, it is possible to calculate the acoustic properties α and c of the material, using equations given in the section"Analysis of Media." When phase cannot be measured, the reflection and absorption coefficients for that particular impedance termination are all that can be determined. References 16 and 50 describe two pulse tubes.

The Standing-Wave Tube

The standing-wave tube is similar to the pulse tube, except that continuous waves are generated instead of pulsed waves. Several methods have been used to obtain the impedance of a sample. For instance, the standing-wave ratio and the position of the first node can be measured; in a tube under pressure, however, this method may present some mechanical difficulties. Another way is to measure the complex pressure at two fixed points spaced a known distance apart along the tube. This is a simple method for closed systems. A variation of this technique is to measure the absolute pressure at two points and the acoustic time-delay between them. References 1, 2, and 47 describe these techniques.

From theory, the cutoff frequency for the first radial mode of a water-filled tube occurs at $f = 0.586c/2a$, where c is the sound speed in water and $2a$ is the inside diameter of the tube. Below this frequency, only the plane-wave mode will propagate down the tube. Above it, although other modes may interfere, the pulse tube can be used (reference 16) by choosing those frequencies where the pulse train is clean and the envelope falls off exponentially, as it does for plane-wave propagation. The cutoff frequency for the first radial mode is a more strict limitation in a standing-wave tube than it is in a pulse tube, because the interfering modes cannot be identified as readily.

Both pulse and standing-wave tubes are well adapted to making measurements at high pressure and controlled temperature; such controls on ambient conditions are employed frequently. All measurements must be at normal incidence; hence, they do not reveal the change in reflection due to change in incident angle. In reference 43, Kuyama and Hasegawa describe a soft-wall, semicircular tube that they constructed and used to measure reflection at oblique incidence. By using modes other than the plane-wave (0,0) mode, they obtained waves incident on the test material at an oblique angle. Because of the sound-soft walls, this approach could not be used under pressure *in statu quo*. Measurements under pressure probably could be made by placing the tube within a suitable pressure chamber.

The Reverberation Chamber

The third technique for making measurements on underwater sound absorbers involves the reverberation chamber. By using a wide band of random noise and measuring the decay rate when the noise is cut off, one can obtain an over-all evaluation of a material that includes characteristics at oblique as well as at normal incidence. This technique has been used extensively in architectural acoustics. A single frequency is used when the frequency-dependent characteristics are desired. For a discussion of this technique, see reference 36.

Panels in Free Field

The fourth, and probably the most widely used technique is that of measuring the reflection of sound from a panel of the material placed in a body of water, as described in reference 20. This method has definite low-frequency limitations. Because the pulse technique must be used to separate the direct from the reflected signal, the lowest usable frequency will be limited to about 2-5 kHz, depending upon panel size and distance between probe and panel. Because of finite panel size, diffraction also will limit the lowest frequency attainable. As a rule of thumb, a panel should be at least two wavelengths across the face at the lowest frequency desired.

The last two techniques require comparatively simple measurements that can be made with a minimum of specialized equipment. They offer the advantage--not available in rigid tubes--that the reflection characteristics can be measured at oblique incidence. The disadvantage is that the measurements are valid for the particular panel under the specific conditions of impedance termination. Extreme caution must be used in extrapolating data to apply to other panel sizes or thicknesses, or to other terminations.

On the other hand, the basic properties of the material can be measured either with the pulse or the standing-wave tube; these properties are independent of the thickness or the termination of the material.

Conclusion

During the course of this survey, several areas needing further research and study have emerged;

1. Materials research is needed, to continue the search for polymeric materials that will yield higher loss factors. Porous materials with greater rigidity need to be identified. The question, "Is there an upper theoretical limit to the lossiness of a material?" should be answered.

2. Further research is needed on viscous-flow absorbing devices. Apparently, devices of this type have not been put to use in actual tanks. The "device" approach, in contrast to the "medium" approach, may prove fruitful.

3. Porous materials probably have received insufficient attention as possible solutions to the problem of broadband absorption. Porous materials have the intrinsic advantage of being virtually unaffected by change in temperature and hydrostatic pressure. Numerous porous materials are available commercially, but because it is difficult to predict the acoustic behavior of a porous material from static data alone, the problem of selecting the best ones--or of designing one--is not easy. (Recall that, to predict the behavior of porous materials from theory, dynamic measurements first have to be made of, at least, the flow resistance and the effective density.) Further work, both on theory and in practice, is needed.

4. At low frequencies (say, less than 5 kHz), the problem of producing significant absorption over several octaves is formidable, particularly in the presence of high hydrostatic pressure. Perhaps an active, rather than a passive absorption process would be a better approach. Beatty, reference 47, describes a method in which the driving voltage and phase of a receiving transducer at one end of a tube can be varied with respect to those of the source transducer at the other end. Thus, the impedance can be varied continuously until it equals the ρc of water, and a plane, progressive wave can be set up within the closed tube. Adjustment is a time-consuming process, but perhaps it can be automated. It may be that the principle can be applied to tanks of other shapes, as well.

5. Research on combination absorbers is needed, as Cramer has suggested in reference 40. Perhaps a combination of a resonant absorber for low frequencies and a broadband absorber for higher frequencies would be an improvement.

6. Up to now, it has been assumed that the sound energy in a tank must be absorbed by some medium or device, but there is an alternative. The energy does not have to be absorbed within the tank if the impedance mismatch at the tank wall can be eliminated and the energy made to pass through the wall into the medium on the other side. Perhaps such a condition could be arranged for the difficult low-frequency range by burying a thin-walled tank in porous, water-saturated soil or other material. The absorption process then would take place outside the tank, rather than

inside, and the tank could be smaller. It seems that a feasibility study is justified.

7. The need to continue research on and development of measurement methods and facilities to evaluate materials for use in underwater sound should be obvious. As new materials or devices become available, they have to be evaluated in terms of the parameters of interest: frequency, hydrostatic pressure, and temperature.

ANNOTATED BIBLIOGRAPHY

This bibliography is chronological. Except as noted, the abstracts and summaries are those of the original author; the notes are those of the authors of this report.

Unclassified Literature

1. L. J. Sivian, "Acoustic Impedance of Small Orifices," J. Acoust. Soc. Amer. 7, 94-101 (1935).

   Abstract: Data are presented giving the measured acoustic reactance and resistance for a number of circular orifices varying in diameter from 1 cm down to 0.034 cm, and for a rectangular orifice 1.9 cm × 0.075 cm. The measurements were made for various particle velocities, the corresponding Reynolds' numbers varying from 0.7 to 3000, roughly. The reactance is found substantially independent of the particle velocity; a formula for computing it is given. The resistance approaches a constant value as the velocity is sufficiently decreased; formulae for computing this "low-velocity" resistance are given. At larger velocities the resistance increases with the velocity. This is discussed from the standpoint of a loss of kinetic energy of flow, acting besides viscosity and turbulence.

   Note: This paper describes a method for measuring acoustic impedance by sampling the complex pressure at two points a known distance apart.

2. W. M. Hall, "An Acoustic Transmission Line for Impedance Measurement," J. Acoust. Soc. Amer. 11, 140-146 (1939).

   Abstract: A method and apparatus are described for rapid and accurate measurement of acoustic impedance in terms of the characteristic acoustic impedance of a tube. The measurement consists of the simple determination of the location and relative magnitude of the maximum and minimum sound pressures along the tube. The impedance of the termination of the tube can then be read directly from a slightly modified hyperbolic tangent chart. Two methods are given for measuring the impedance of acoustic elements with cross sections different from that of the measuring tube.

3. J. van den Eijk and C. Zwikker, "Absorption of Sound by a Porous Material," Physica 8, 149-158 (1941).

   Summary: The porosity and air resistance of a wood-fiber plate and a plate of acoustic plaster were measured. The acoustical absorption coefficient to be expected was calculated from these measured values and older theories. These absorption coefficients then were directly measured--for perpendicular incidence by an interference

method, and for incidence from all directions by a reverberation method with a constant-tone sound signal. Figures 5, 7, and 8 show to what extent theory and experiment agree. Obviously, the theory is inadequate. (Translated from Authors' German summary)

Note: In several succeeding papers, the authors introduce a new theory of absorption in porous materials that postulates that the three parameters porosity, flow resistance, and structure factor are needed to describe the acoustic properties of rigid porous materials. Supporting data are given. This work is reviewed and elaborated upon in reference 9.

4. A. E. H. Love, *The Mathematical Theory of Elasticity* (Dover Publications, New York, 1944).

5. L. L. Beranek, "Acoustical Properties of Homogeneous, Isotropic Rigid Tiles and Flexible Blankets," J. Acoust. Soc. Amer. 19, 556-568 (1947).

Abstract: Studies on rigid acoustical tiles and soft blankets are described in this paper. It is shown that two waves travel through the material--one primarily airborne and the other primarily structureborne. From a knowledge of the density of the sample, the volume coefficients of elasticity of the air and of the skeleton of the material, the porosity, the air-flow resistance, the inter-fiber frictional resistance, and the structure factor, the propagation constants of each of these waves can be calculated. The experimental results indicate that the theory is useful in calculating the performance of the flexible, airplane-type of blankets over the entire audible frequency range. For rigid tiles, however, the theory appears to fail at frequencies above 1000 c.p.s. if the flow resistance is high, and it fails at all frequencies for materials with low flow resistance. Experiment shows that the condensations and rarefactions of the gas in blankets takes place isothermally at low frequencies and adiabatically at high. The transfer from one state to the other occurs gradually in the 100- to 2000-c.p.s. region. A more complete theory is required to explain the effects of thermodynamic and viscous losses on the propagation constant of rigid materials.

6. R. J. Urick, "The Absorption of Sound in Suspensions of Irregular Particles," J. Acoust. Soc. Amer. 20, 283-289 (1948).

Abstract: The greater part of the absorption of sound in aqueous suspensions of small spherical particles can be attributed to the viscous drag between the fluid and the particles in the sound field. The absorption resulting from this process is found to agree with that obtained by Lamb in another manner. The applicability of the theoretical result to suspensions of irregular particles is examined by means of measurements on sand and kaolin suspensions, using a pulse-reflection method at megacycle frequencies. Approximate agreement with the idealized theory is found as the particle size, viscosity, and frequency are varied.

Note: Urick derives a theoretical expression for the attenuation of sound in suspensions and verifies it experimentally.

7. W. P. Mason and F. H. Hibbard, "Absorbing Media for Underwater Sound Measuring Tanks and Baffles," J. Acoust. Soc. Amer. 20, 476-482 (1948).

Abstract: By using absorbing walls surrounding a small body of water, measuring tanks have been produced which will determine the directional properties of underwater sound instruments down to a level of 25 dB below the direct beam. These absorbing media are constructed by inserting fine mesh screen or packed copper wadding in a viscous liquid such as castor oil. These obstructions result in an enhanced viscous action which is nearly independent of frequency above 10 kilocycles. A six-inch wall can reduce the reflections by 20 dB. Tanks using such absorbing media were used for testing transducers at the manufacturing plant and were used for determining the approximate characteristics of small sized instruments. Absorbing media were also used in the sound transparent dome housing the transducer and in the back of the QJB transducers.

Note: This paper describes the absorber used in several tanks during World War II. The low-frequency limit depends upon the density of the screening material, because the screen tends to be dragged along by the viscous liquid.

8. B. V. English and C. L. Darner, "Reduction of Reverberation in a Water-Filled Steel Test Vessel by Use of a Porous Material," J. Acoust. Soc. Amer. 20, 587(A) (1948).

Abstract: A porous material has been used in a steel test tank at the Underwater Sound Reference Laboratory to decrease the reverberation time of the tank. Data will be presented showing the effects of frequency and pressure on the underwater sound absorption coefficient of the material. Measurements of performance characteristics of underwater electroacoustic transducers are made in the test tank under hydrostatic pressures up to 300 pounds p.s.i. Calibration work in this tank requires the use of the pulse method. For present research projects, the reverberation level in the tank must be at least 40 dB below the level of the directly received pulse. Before using the porous material, the reverberation level at the time of the received pulse was down only 5-30 dB in the frequency range 10-150 kc. Use of the absorbing material in the tank has reduced this level by as much as 40 dB, thus affecting the present margin of 40-70 dB.

Note: The material referred to is concrete, which was later superseded by the improved absorber Insulkrete.

9. C. Zwikker and C. W. Kosten, *Sound Absorbing Materials* (Elsevier Publishing Co., Inc., New York, 1949).

Note: This book provides a good introduction to the theory of rigid and elastic porous media. Though written for the air acoustician, it is, nevertheless, quite useful in underwater sound.

10. P. W. Bridgman, *The Physics of High Pressure* (G. Bell and Sons, Ltd., London, 1949).

11. A. Schoch, "Theory of Lining for Anechoic Rooms Based on the Principle of Gradual Transition," in "Noise and Sound Transmission," Proc. Phys. Soc. (London)(1949), pp. 167-173.

Abstract: Following a consideration of the reflection of sound waves from uniform plates of porous material, an indication is given of the theoretical approach to the design of pyramid- or wedge-shaped elements of porous material projecting from the boundary surface for minimizing sound reflection. Curves are given for a linear wedge structure showing how the reflection factor depends on the frequency parameter, flow resistance parameter, and on the position in the structure. [3017, Physics Abstracts 53, 375 (1950)].

12. E. Meyer (Ed.), *Sound Absorption and Sound Absorbers in Water*, Department of the Navy, Bureau of Ships, NAVSHIPS 900,164 (1950), Vol. 1.

Note: This reference is a summary of the work done during World War II by the Germans on the development of both resonant and broadband absorbers. It is a tribute to their efforts, as well as an acknowledgment of the difficulty of the problem, that present-day absorbers are, for the most part, minor modifications of their original designs.

13. W. J. Trott and C. L. Darner, "Measurement of the Acoustic Properties of Sound Absorbent Panels at High Hydrostatic Pressures," J. Acoust. Soc. Amer. 22, 681(A) (1950).

Abstract: Measurements of underwater sound reflection and transmission properties of several sound-absorbent materials in the frequency range from 10 to 150 kilocycles per second at hydrostatic pressures up to 350 pounds per square inch are presented, and the method of measurement is described.

Note: The material was what is now called Insulkrete. The data show that the sound absorption is unaffected by pressure. A more thorough evaluation is given in reference 19.

14. E. Meyer and K. Tamm, "Breitbandabsorber für Flüssigkeitsschall," Acustica 2, AB91-104 (1951).

Summary: A new wide-band absorber for waterborne sound to line measuring tanks is investigated experimentally and theoretically. The frequency range is 5 to 50 kc/s. The absorber consists of rubber-elastic materials the aftereffect of which is used for the energy absorption and which are made more compressible than rubber

or water by making them porous or by inserting larger holes. Parallel ribs of the material form parallel ducts, in which the sound energy is being absorbed; to match the characteristic impedance of the medium and the absorber the duct walls are wedge-shaped at their exposed sides.

15. W. Kuhl, "Über Messungen in einem schallschluckend ausgekleideten Wasserschall-Messbecken," Acustica 2, AB140-144 (1951).

Summary: The sound field in a measuring tank for waterborne sound lined with an absorber is investigated experimentally and is computed in the frequency range of 4 to 80 kc/s.

16. W. S. Cramer and K. S. Bonwit, "Pulse Tube for Acoustic Measurements," Naval Ordnance Laboratory Report NAVORD 2257, 30 April 1952.

Abstract: An apparatus was constructed with which the acoustic impedance and other acoustic properties of a sample in water can be measured at normal incidence. It consists essentially of a thick-walled steel tube, 6 feet long with an internal diameter of 2¼ inches, which is mounted vertically and filled with water. A crystal transducer, mounted at the bottom of the tube, produces a pulsed acoustic signal which travels up the tube. At the top, this signal impinges on the material under study and is reflected with characteristic changes in amplitude and phase back to the transducer which then acts as a receiver. The resulting pattern is viewed on a cathode ray oscilloscope. The specific acoustic impedance of the surface is calculated from the reduction in amplitude and change in phase experienced by the sound wave on reflection. These measurements are made electronically by a null method by comparing the properties of the unknown sample with a control sample which is an essentially perfect reflector. The present frequency range is from 10 to 40 kc/s but with an additional transducer, it could be extended to 100 kc/s. The pulse repetition frequency is 60 pulses per second and the pulse duration can be varied from less than 0.5 to 2.0 milliseconds. The temperature in the tube can be controlled between 10°C and 70°C and the hydrostatic pressure can be varied from atmospheric pressure to 250 psi, or more.

17. H. Kolsky, *Stress Waves in Solids* (Oxford University Press, London, 1953).

Note: This book is a highly readable account of the theory of wave propagation in homogeneous materials.

18. W. S. Cramer, "Theoretical Study of Underwater Sound Absorbing Layers," Naval Ordnance Laboratory Report NAVORD 2803, 1 Jun 1953.

Abstract: The acoustic impedance of a layer of material mounted against a rigid backing can be derived theoretically. This theory is used to study the behavior of the sample as an absorber of

underwater sound. The parameters which must be known are: the frequency, the thickness of material, and the acoustic propagation constants. If the thickness of the layer is measured in wavelengths of sound in the material, the echo reduction increases with thickness to a peak at less than one quarter wavelength. This is followed, as the thickness continues to increase, by a low point and then another peak and so on with gradually decreasing differences until the echo reduction becomes constant with thickness. The thickness needed to reach this constant region decreases as the loss factor increases. However, the actual value of the echo reduction attained is less for the higher loss materials because of impedance matching difficulties.

A layer of cellular rubber can be designed to operate at the first peak mentioned above. The maximum echo reduction possible is determined by the loss factor of the material but the thickness to achieve this maximum must be adjusted for the material and frequency used. Several coatings based on this principle have been under extensive study and development at other laboratories.

Coatings can also be designed to operate in the constant reduction region mentioned above where the coating is said to be "infinitely thick." Layers of this sort are less sensitive to variations in thickness, frequency, pressure, temperature, etc., than those operating at the first peak. However, they are more difficult to design in some ways and may require thicknesses of several centimeters. Original research at this Laboratory indicates that metal-loaded rubber should be used for such coatings. This material appears to be able to achieve moderate losses in the material while at the same time giving a good acoustic match to water. Experimental data on a typical metal-loaded sample support these conclusions. The behavior of these various coatings as a function of thickness and frequency has been studied experimentally on controlled samples and found to agree reasonably well with theory. The behavior as a function of pressure and temperature can only be studied experimentally since existing theory is inadequate to explain variations in these two parameters. Measurements on coating materials show that increased static pressure produces a higher modulus and a lower loss factor. A decrease in temperature also gives a higher modulus but the loss factor has a maximum value as a function of temperature.

Note: In addition to being a good theoretical study of absorption, the report describes the type of resonant absorber developed in this country during World War II by the Acoustics Laboratory at the Massachusetts Institute of Technology. The approach was to use a sprayed-on rubber that entrapped air voids.

19. C. L. Darner, "An Underwater Sound Absorber for an Anechoic Tank," Navy Underwater Sound Reference Laboratory Research Report No. 31, 15 Sep 1953.

Abstract: The work done at the USRL on the measurement of the sound-absorbing properties of various materials in water at hydrostatic pressures from 0 to 1000 psig in the frequency range 10 to 150 kc is summarized. Data are presented to show the improvement obtained by lining three different test vessels with the sound-absorbing material Insulkrete--a pine sawdust-Portland cement composition. Instructions are included for the construction of this material.

Note: This report describes the development and evaluation of a widely-used porous absorber that is insensitive to changes in temperature and pressure.

20. A. Heller, "Underwater Anechoic Tank Linings," Naval Ordnance Laboratory Report NAVORD 2989, 10 Nov 1953.

Abstract: An investigation of structured linings employing the principle of a gradual impedance transition from water to a sound-absorbent material has been made. Prototype metal-loaded butyl rubber linings have been developed which consist of a molded panel of closely-packed right-circular cones and an integral backing layer. Reflection characteristics were measured for three samples having this structure but differing in the type of metal loading. In addition, measurements were made on plane samples of each type of rubber, and also on samples of Fafnir, Insulkrete, and canvas. The technique consisted of subjecting the test panel to normally incident pulse-modulated sound and measuring the reflected sound pressure with a rotating probe hydrophone. The test panel was backed by a perfectly-reflecting flat plate which also was used as a reference reflector. By this method it was possible to obtain the reflected sound intensity as a function of polar angle (reflectivity pattern) and from this the scattering and absorption were computed. An aluminum-loaded butyl rubber specimen with a multiple cone surface had the best overall anechoic characteristics of all samples tested, over a frequency range from 50 to 250 kc. Measurements on this sample were made from 20 kc to 1 Mc. The sound reflection coefficient (ratio of total acoustic power reflected to the total incident power) was at least -20 dB over the frequency range covered, and at 200 kc the coefficient had a maximum value of -32 dB. The maximum reflected intensity was at least -23 dB from 20 kc to 1 Mc and was -38 dB at 200 kc.

21. W. S. Cramer, "Acoustic Properties of Metal-loaded Rubbers," Naval Ordnance Laboratory NAVORD Report 3756, 9 Aug 1954.

Abstract: Properly formulated mixtures of metal particles and butyl rubber when molded into a layer ¼" or more thick and adhered to a rigid backing, become good echo reducing coatings for underwater sound. In the study reported here metal-loaded rubber mixtures were investigated extensively to find out why such acoustic losses occur and how to improve the echo reduction. The chief experimental technique was to measure the acoustic impedance of a rigidly backed

sample in an acoustic pulse tube and then to calculate the velocity and attenuation in the material from theoretical relationships. The variations in the propagation constants were first studied as a function of the type of metal loading, particle size, concentration, and method of cure. Emphasis was put on loadings of lead and aluminum particles with maximum dimensions of 0.004 cm to 0.100 cm and on concentrations of from 25 to 500 parts of the metal by weight to 100 parts of the rubber. It was found that the addition of metal particles increased the attenuation and decreased the velocity in the mixtures at rates depending on the type of metal and the cure conditions. There seemed to be no significant dependence on particle size in the range considered. The acoustic properties were very sensitive to the temperature and pressure during the cure, as well as to the other cure conditions.

The impedance measurements were made mostly near 20 kc at room temperature and at atmospheric pressure. Some studies were made to show the variations in the acoustic properties with temperature over the range 50°F to 90°F and with hydrostatic pressures up to 200 psi. It was found that a decrease in temperature or an increase in hydrostatic pressure resulted in increased velocity and decreased attenuation, the rates of change again being characteristic of the material. The velocity was found to increase and the attenuation to decrease with time after cure with both values becoming approximately constant in about a year.

The measurements referred to above along with microscopic examinations indicated that some gas pockets were produced accidentally in the material during manufacture and that this gas content had a large effect on the acoustic properties of the mixture. A gas content was therefore deliberately introduced, with a chemical blowing agent, in a series of samples so that the amount of gas could be controlled and the effect of the gas content could be studied systematically. The results of acoustic measurements showed that with increasing gas content (up to 10 percent, at least), there resulted decreasing velocity, decreasing bulk modulus, increasing attenuation, and increasing loss factor. The data (bulk modulus as a function of gas content) showed good agreement with a theory presented in the literature for gas contents up to about 6 percent. This theory gives the bulk modulus of an expanded material in terms of the gas content of the mixture and the shear and bulk moduli of the unexpanded material. For a given gas content the acoustic properties also depend on the properties of the rubber matrix. This effect was studied by using two different rubber mixtures. One was the butyl rubber with metal loading but only such additional chemicals as were needed for curing. The other was the same mixture plus a reinforcing filler of carbon black. Comparative measurements, with the same gas content and metal loading, showed that the mixture with carbon black had a higher bulk modulus, higher velocity, lower attenuation, and lower loss factor than the one without carbon black.

This study showed that the acoustic attenuation of the metal-loaded butyl mixtures was primarily due to a gas content either introduced deliberately (with a blowing agent) or through some chemical reaction in the rubber due to the metal. The decrease in velocity in the mixture with loading, due both to the higher density and to the gas content, was at least partially compensated for by an increase in density so the product of density and velocity (ρc) usually did not change appreciably. The outstanding feature of the metal-loaded mixtures is the good acoustic match between material and water along with an appreciable attenuation in the material. Metal-loaded butyls have been used as layer-type anechoic coatings and have also been molded into cone-shaped structures of high echo-reduction for use as tank linings.

Note: Cramer's viewpoint on the loss mechanism in metal-loaded rubbers appears to be generally accepted.

22. P. Tamarkin and R. K. Eby, "Tank Wall Lining for Underwater Sound Use," J. Acoust. Soc. Amer. 27, 692-698 (1955).

Abstract: An anechoic lining for underwater sound use can be made from waterproofed, rubberized, horsehair batting. It decreases the reflectivity 20 dB below that obtained from a steel wall over a frequency range from 100 kc to 400 kc and for a wide range of angles of incidence. It is inexpensive, easily installed, and can be used for several 8-hour periods before additional waterproofing is necessary.

23. J. V. Bouyoucos, "A Two-Probe Method for Measuring Acoustical Impedance," internal memorandum of Acoustics Research Laboratory, Harvard University, 8 Dec 1955.

Note: This paper describes a practical technique for measuring acoustic impedance with two fixed probes; reference 47 describes an underwater sound measuring facility using this technique to establish plane progressive waves.

24. I. S. Sokolnikoff, *Mathematical Theory of Elasticity* (McGraw-Hill Book Company, Inc., New York, 1956), 2nd ed.

25. M. A. Biot, "Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid. I. Low-Frequency Range," J. Acoust. Soc. Amer. 28, 168-178 (1956).

Abstract: A theory is developed for the propagation of stress waves in a porous elastic solid containing a compressible viscous fluid. The emphasis of the present treatment is on materials where fluid and solid are of comparable densities as for instance in the case of water-saturated rock. The paper denoted here as Part I is restricted to the lower frequency range where the assumption of Poiseuille flow is valid. The extension to the higher frequencies will be treated in Part II. It is found that the material may be described by four nondimensional parameters and a characteristic frequency. There are

two dilatational waves and one rotational wave. The physical interpretation of the result is clarified by treating first the case where the fluid is frictionless. The case of a material containing a viscous fluid is then developed and discussed numerically. Phase velocity dispersion curves and attenuation coefficients for the three types of waves are plotted as a function of the frequency for various combinations of the characteristic parameters.

26. M. A. Biot, "Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid. II. Higher Frequency Range," J. Acoust. Soc. Amer. 28, 179-191 (1956).

Abstract: The theory of propagation of stress waves in a porous elastic solid developed in Part I for the low-frequency range is extended to higher frequencies. The breakdown of Poiseuille flow beyond the critical frequency is discussed for pores of flat and circular shapes. As in Part I the emphasis of the treatment is on cases where fluid and solids are of comparable densities. Dispersion curves for phase and group velocities along with attenuation factors are plotted *versus* frequency for the rotational and the two dilational waves and for six numerical combinations of the characteristic parameters of the porous systems. Asymptotic behavior at high frequency is also discussed.

27. W. S. Cramer and T. F. Johnson, "Underwater Sound Absorbing Structures," J. Acoust. Soc. Amer. 28, 501-502(L) (1956).

Abstract: Some historical background on the use of metal-loaded rubbers for acoustical purposes is presented. Data are given which show that the performance of sound absorbing wedges is improved by adding air-filled cylindrical holes.

Note: This study was an extension of a similar one reported by the Germans in reference 12. The conclusions are consistent with the earlier study.

28. E. G. Richardson (Ed.), *Technical Aspects of Sound* (Elsevier Publishing Co., New York, 1957), Vol. II, Chaps. 6 and 7.

29. N. B. Miller, "Reflections from Gradual Transition Sound Absorbers," J. Acoust. Soc. Amer. 30, 967-973 (1958).

Abstract: Reflections from gradual transition linings for anechoic tanks are treated theoretically by considering the propagation of compressional waves in stratified media. The reflections are the combined effect of backscattering in the transition region and round trip transmission through the lining resulting from imperfect absorption of sound by the lining. Sound propagation in the inhomogeneous transition region is fairly complex; the incident energy is absorbed and scattered back and forth, and phase interference occurs in a complicated fashion. If the lining is viewed as a succession of arbitrarily thin panels, however, then the pressure is readily

separated into progressive waves, and it is shown that each increment of distance "backscatters" a fraction of the total incident wave that is proportional to the logarithmic derivative of the characteristic impedance. Certain typical types of linings are considered in detail to determine theoretically the proportions of transition width to total lining width producing minimum reflections. The theoretical results are compared with experimental data for a cone type underwater lining, showing that the one-dimensional theory gives useful results for cone and wedge linings.

30. N. S. Narayanan, "Absorption of Sound Under Water by Wedges," J. Inst. Telecomm. Engrs. 5, 89-92 (1959).

Note: The author measured the reflectivity of several patterns of SOAB wedges and concluded that a spacing of 2.5×2.5 cm (distance between rows and columns of wedges) give the best absorption in the frequency range 14 to 30 kHz.

31. R. F. Marboe and R. W. Farwell, "Absorption and Reflection Characteristics of a Water-Filled Anechoic Tank," J. Acoust. Soc. Amer. 31, 1573(A) (1959).

Abstract: Measurements made in the water-filled anechoic tank at the Ordnance Research Laboratory indicate that the lining of Insulkrete wedges absorbs more than 99% of the direct signal energy at frequencies between 30 and 105 kc. Between 20 and 30 kc the tank is better than 90% absorbent. The absorption falls off considerably below 20 kc. Comparisons of the reverberation and the reflection measurements in the unlined tank are included. At frequencies above 40 kc the apparent plane of reflection in the lined tank is at the tip of the wedges.

32. E. Meyer, W. Schilz, and K. Tamm, "Über den bau eines reflexionsfreien Wasserschall-Messbeckens," Acustica 10, 281-287 (1960).

Summary: A water basin with the dimensions 7 m × 4 m × 4 m was constructed for measurements with water-borne sound. The walls of this basin are coated with absorbers effective in the frequency range from 5 to 70 kc/s. These broad-band absorbers consist of a system of parallel, wedge-shaped rubber plates made up of three layers of rubber glued together. The center sheet is perforated with circular holes (diameter 4 mm, hole density 4%). There are three types of wedges differing in length (7, 15, and 20 cm) covering the frequency range from 5 to 70 kc/s. The reflection factor related to amplitude remains below 10% in this frequency range. The excellent acoustical properties of the unechoic measuring basin are confirmed by the very small standing wave ratio for all frequencies.

33. R. A. Rubega and A. Culver, "Some Experiments in Underwater Sound Absorption," J. Acoust. Soc. Amer. 33, 1680(A) (1961).

Abstract: This paper discusses some experimental techniques for the measurement of sound absorbing materials in the 2- to 10-kc range. The experimental technique discussed is that of decay time measurements of a reverberant chamber. Several different kinds of signals have been used--namely pulsed sine waves, pulsed noise, and an impulse signal generated by the discharge of an underwater spark. The spark source was found the most convenient to use. Though at present the measurements are not as precise as those obtained in air-filled reverberation chambers, the method does allow a quantitative comparison of underwater absorbing materials. An analysis of precision of the method will be given. Other methods for measuring absorption will be described briefly. (Sponsored by the Office of Naval Research, Code 411.)

34. M. Okushima, "A New Tube Method for Measuring Complex Pressure Reflection Coefficients of Absorbers in Water," J. Acoust. Soc. Jap. 17, 213-222 (1961). In Japanese.

Abstract: The author devised a new tube method for measuring the complex pressure reflection coefficient in water, constructed the apparatus, and measured several samples. This method is a sort of the stationary wave method.

In this set up, the bottom surface of a vertical steel tube with thick wall (length 400 mm, inner radius 17.5 mm, wall thickness 6 mm) is driven at one of the longitudinal resonant frequency (about 9, 18, 27 and 36 kc) of a Langevin type transducer of barium titanate, and the stationary wave field is formed in the water column between the bottom surface and the sample inserted in the tube from the top.

By this method, the principle that the mechanical impedance toward the sample at the bottom takes the minimum or the maximum values, when the sample is moved up and down and as the bottom surface coincides with the node or the loop plane of pressure in the stationary wave field is used. Namely, the amplitude of the complex reflection coefficient is derived from values of these two impedances, which are obtained by measuring the reaction to the transducer surface from the field in the tube, while the phase of the complex reflection coefficient is derived by measuring the distance between the sample and the pressure node plane in which the mechanical impedance takes the minimum value.

Two methods, the motional admittance method and the vibrometer method, were devised for the purpose of measuring the mechanical impedance.

The transducer for the vibrometer method has two barium titanate elements for driving and for measuring the velocity amplitude, and it is so designed as to become a multiresonant transducer which vibrates with the same intensity for the most part and is capable of being

employed for measuring with equal easiness at four resonant frequencies (9, 17, 27 and 36 kc).

Wooden wedges is generally used for the lining of the unechoic water tank in this country, so the author measured the reflection coefficient of wooden (pine) wedges and plates by this apparatus.

35. G. H. F. Gardner, "Extensional Waves in Fluid-Saturated Porous Cylinders," J. Acoust. Soc. Amer. 34, 36-40 (1962).

Abstract: Pochhammer's method of analysis for waves in circular cylinders is extended to Biot's theory for an elastic porous solid saturated with a compressible viscous fluid. Attention is given mainly to slender rods vibrating at low frequencies. The boundary condition of zero stresses on the curved cylindrical surface is used to derive the frequency equation from which phase velocity and attenuation may be obtained. In general, two types of extensional waves exist, just as there are two types of dilatational waves. The attenuation per unit length of the first kind of wave is proportional to the square of the frequency at low frequencies except when the wavelength of dilatational waves of the second kind is about half the perimeter of the cylinder. In the neighborhood of this frequency the attenuation may show a maximum. Waves of the second kind behave like a diffusion phenomenon, except in the same neighborhood.

36. R. A. Rubega and E. I. Prasse, "Study of Underwater Acoustic Absorbers," Research Department, General Dynamics/Electronics, Rochester, N. Y., Final Report on Contract NOnr 2646(00), 15 Mar 1962.

Abstract: A theoretical and experimental study of possible new methods of underwater sound absorption in the frequency range from 2 to 10 kc was made. Four methods of determining sound absorption were considered: (1) measurement of the flexural vibration of damped plates under excitation by an incident sound wave; (2) measurement of decay time in a small-scale reverberation tank; (3) measurement of direct echo reduction in a full-scale sonar tank; and (4) energy accounting techniques, both in air and under water. With Method (1), it was found that no direct indication of flexural motion could be observed for the plates tested with the pickup and instrumentation used. Under Method (2), qualitative comparisons of various absorbing materials are presented. Under Method (3), results were obtained for a "forest" type of absorber system consisting of neoprene strips; while under Method (4), results are given for one type of absorbing plate. Limitations and possible sources of error for all methods are discussed.

37. M. A. Biot, "Mechanics of Deformation and Acoustic Propagation in Porous Media," J. Appl. Phys. 33, 1482-1498 (1962).

Abstract: A unified treatment of the mechanics of deformation and acoustic propagation in porous media is presented, and some new results and generalizations are derived. The writer's earlier

theory of deformation of porous media derived from general principles of nonequilibrium thermodynamics is applied. The fluid-solid medium is treated as a complex physical-chemical system with resultant relaxation and viscoelastic properties of a very general nature. Specific relaxation models are discussed, and the general applicability of a correspondence principle is further emphasized. The theory of acoustic propagation is extended to include anisotropic media, solid dissipation, and other relaxation effects. Some typical examples of sources of dissipation other than fluid viscosity are considered.

38. M. A. Biot, "Generalized Theory of Acoustic Propagation in Porous Dissipative Media," J. Acoust. Soc. Amer. 34, 1254-1264 (1962).

Abstract: The theory of acoustic propagation in porous media is extended to include anisotropy, viscoelasticity, and solid dissipation. A more refined analysis of the relative motion of the fluid in the pores is also developed by introducing the concept of viscodynamic operational tensor. The nature of this operator is analyzed by applying variational and Lagrangian methods. Viscoelasticity and solid dissipation are introduced by applying the correspondence principle as derived from thermodynamics in earlier work by the author. Various dissipative models are discussed and the corresponding operators and relaxation spectra are derived. The physical chemistry of the multiphase porous medium including surface effects lies within the scope of the thermodynamic theory. The nature of thermoelastic dissipation and electrokinetic effects in relation to the thermodynamic theory is also brought out.

39. C. L. Wakamo, "Low-Frequency Anechoic Tank for Underwater Sound Studies," Acoustical and Seismological Laboratory, University of Michigan, Ann Arbor, Report No. 2784-8-T, November 1962.

Abstract: This report describes the building (in conjunction with laboratory studies of underwater acoustics) of an anechoic tank. The walls were made highly absorptive by using a combination of high-density concrete and SAPER T absorber material. Refined absorption was effected by the elimination of all free air-water interfaces and the exclusion of air from the space between the coating and wall structure. The tank has performed effectively at frequencies as low as 200 cps. The particular combination of SAPER T and wall structure was evaluated by measurements of standing wave ratio. Problems of design and maintenance were easily solved, and isolation was provided from structure-borne noise. An incidental feature is the tank's ready convertibility for reverberation studies.

40. W. S. Cramer, "Sound-Absorbing Linings for Waterfilled Tanks," Sound 2, No. 4, 18-24 (1963).

Note: Cramer discusses various types of linings that have been used successfully and suggests that a combination of a resonant lining

for the low frequencies and a broadband absorber for the higher frequencies is an intriguing approach.

41. P. D. Ritchie (Ed.), *Physics of Plastics* (D. Van Nostrand Company, Inc., Princeton, N. J., 1965), Chap. 2 and Chap. 9.

Note: Because this book describes the physical behavior of high polymers, it may be of interest in connection with the discussion of resonant absorbers, particularly the chapters cited.

42. W. Meeks, "A Study of Resonant Absorbers for Underwater Sound," Physics Department, Rose Polytechnic Institute, Terminal Report under Contract Nonr 3255(01), January 1965.

Summary: In the first part of the work a simple model of a resonant absorber is proposed from which is derived an expression relating the acoustic impedance at the surface of the absorber with the dynamic modulus of the material from which it is made. Results are presented of measurements of the impedance and dynamic moduli of resonant absorber samples having rectangularly shaped holes, to which the model presumably applies. From the impedance measurements which were made using pulse techniques it is established that the real and imaginary parts of the acoustic admittance at the sample face are linear functions of the number of holes per unit area, as predicted by the original theory of the absorber proposed by Meyer, etc. The real part, however, unlike the results of Meyer, has a non-zero positive intercept. Difficulties in obtaining reliable dynamic moduli values from the measurements of the attenuation and velocity of torsional waves in thin rods, and the small range of dynamic moduli of the materials used made it possible to make a decisive test of the proposed model of the absorber.

In Part II a theoretical study is made of a resonant absorber consisting of a thin rubber membrane cemented or clamped over a metal disc in which circular holes have been bored. An expression for the specific acoustic admittance of this membrane type absorber is derived in terms of the tension in the membrane, the surface density, the damping constant, the radius of the holes, the number of holes per unit area, and the mass and thickness of the disc. The anechoic properties of such a surface is investigated for various values of the different parameters involved.

Experimental procedures and apparatus used for the various measurements are also presented.

Note: Meeks' data, though not extensive, appear to agree with his theory. Moreover, the theory relates the acoustic impedance of a resonant absorber to the fundamental dynamic properties of the rubber, which Meyer's theory (see reference 12) did not do.

43. T. Kuyama and A. Hasegawa, "Measurement of Acoustic Properties of an Underwater Sound Absorbing Material at an Oblique Incidence," Memoirs of the Defense Academy, Japan 4, 233-244 (1965).

Abstract: By the use of the mode propagation of waves of sound in a water tube of nearly semi-circular cross section whose upper plane surface is a free surface of water and whose semi-circular wall is made of a thin foil of plastic material, the acoustic properties of an underwater sound absorbing material at an oblique incidence of waves are measured. The theoretical considerations and the experimental results of a sound reflection coefficient and acoustic impedance of a wedge-shaped material made of wood are indicated.

Note: This novel method of measuring reflection at oblique incidence appears promising.

44. W. M. Prest, Jr., T. D. Cohen, and E. J. Janowski, "A Comparison of Some Underwater Anechoic Materials," Naval Underwater Ordnance Station Technical Memorandum No. 352, July 1965.

Abstract: Some reflection characteristics of wooden wedges, rubber wedges, and flat samples of redwood and Insulkrete were investigated to determine their suitability for lining an acoustic tank. Results show that, in general:

1. Wedges of a sound absorptive material reduce reflections more than a flat surface of the same sound absorptive material.

2. The wooden wedges tested reduce reflection more than rubber wedges.

3. The fir wedges reduce reflection more than redwood wedges.

It is recommended that the dynamometer pit be lined with fir wedges to more effectively handle underwater tests.

45. J. E. White, "Reflections from Lossy Media," J. Acoust. Soc. Amer. 38, 604-607 (1965).

Abstract: A simple analysis shows that, when a transient plane wave in an elastic medium is reflected at a plane boundary with a lossy medium, the transient waveform of the reflection is affected by the loss parameters of the second medium. If the attenuation in the second medium is small, and if the ρc products of the two media are matched, then the reflected waveform is the convolution of the incident waveform, with the integral of the Fourier transform of attenuation as a function of frequency. Thus, attenuation for a lossy solid or liquid can be obtained by this external-pulse technique. Where attenuation is some simple function of frequency, its Fourier transform is some recognized generalized function. Sample waveforms

have been observed using airborne sound in specially prepared tubes; good qualitative agreement with predicted waveform was obtained.

Note: This technique is useful where the material is inacessible for direct measurement, but it is not likely to be used as a primary method because of the lack of accuracy.

46. E. Böcher, "Untersuchungen zur Absorption von Wasserschall im Frequenzbereich von 1 kHz bis 6 kHz," Acustica 15, 418-425 (1965).

Summary: The present paper gives a survey of the various possible absorbing arrangements for water-borne sound in the frequency range between 1 kc/s and 6 kc/s. Several different arrangements were built and the magnitude and phase angle of their reflection coefficient were measured in a rigid Kundt's tube. With systems consisting of mass and spring elements a high absorption could be obtained only within a narrow frequency range. Absorbing arrangements where the sound particle velocity is suitably transformed by fluid flow gave useful results in the frequency range given above. Therefore, as further part of the investigations the input impedance of fluid films with layer thicknesses from 1.5 mm to 0.1 mm was measured by help of an aluminium bar tuned to longitudinal $\lambda/2$ resonance. The measured results agree well with theoretical values.

Note: This paper introduces the unique "velocity transformation" method of obtaining absorption below 5 kHz.

47. L. G. Beatty, R. J. Bobber, and D. L. Phillips, "Sonar Transducer Calibration in a High-Pressure Tube," J. Acoust. Soc. Amer. 39, 48-54 (1966).

Abstract: A unique tube facility for the calibration of sonar transducers under hydrostatic pressures to 8500 psi is described. The pressure vessel consists of the modified liner from a 16-in. gun. The liner is 50 ft long and has an inside diameter of 15 in. An [illegible]tive-impedance principle is applied to establish plane progressive [illegible]es within the tube. Resonant transducers can be calibrated in [illegible]ne frequency range 100-1500 Hz; nonresonant, hard transducers can [illegible]e calibrated in the range 40-1500 Hz.

Note: The method used to verify plane waves is to measure the impedance, using fixed probes at various intervals along the tube.

48. "Test Methods Used to Determine the Acoustic Properties of Material While in a Water Medium," Engineering Societies Library, New York, May 1966.

Note: This is a bibliography with 78 references.

49. G. S. Bennett, "Measurement of Acoustic Properties of Materials," Goodyear Aerospace Corporation, GER 12442-B, July 25, 1966.

Note: The author is concerned primarily with transmission loss through panels, and the agreement between theory and experiment.

50. G. A. Sabin, "Measurement of Acoustic Impedance at High Hydrostatic Pressure," J. Acoust. Soc. Amer. 40, 1345-1353 (1966).

Abstract: The theory, design, and operation of a system for the measurement of acoustic impedance at hydrostatic pressures to 10 000 psig are described. The system is a pulse tube featuring the use of coherent pulses. The acoustical characteristics of materials are determined from measurements made on small samples (2 in. diam × ~ 6 in. long). Three different measurement methods are discussed.

51. E. Meyer, K. Brendel, and J. Richter, "Absorption von Wasserschall durch erzwungene Wechselströmung von Flüssigkeiten," Acustica 19, 8-20 (1967-68).

Summary: The present paper introduces thin-layered absorbers of water-borne sound for frequencies above 250 Hz, in which the losses necessary for absorption are obtained by forced alternating flow of viscous fluids with which there is a transformation of particle velocity. Using streaming fluids of a viscosity of some 10^3 cP, fluid damped single and coupled resonant systems yield good absorption in a frequency range of up to three octaves. When fluids of smaller viscosity are used, difficulties arise in the adjustment of the necessarily smaller thickness of layer and thus in matching the absorber. Non-Newtonian properties prevent broad-band matching with fluids of viscosities considerably large than 10^3 cP.

In the frequency range of 250 Hz to 4 kHz the impedance measurements are carried out in a pressure chamber, while a pulse-tube is used between 4 kHz and 21 kHz.

52. V. V. Ivanov, Yu. A. Medvedev, and B. M. Stepanov, "Sound Propagation in a Wet Porous Medium," Soviet Physics--Acoustics 14, 51-53 (1968).

Abstract: The propagation of sound in a wet porous medium is analyzed at low frequencies. It is established that transverse waves are more rapidly damped than longitudinal waves. The velocity of sound and absorption coefficient are calculated.

Note: This analysis is for a wet, but not saturated, medium; hence, the fluid viscosity is not considered.

53. K. Brendel and K. Hinsch, "Wasserschall-Resonanzabsorber mit Relaxationsverlusten in Hochpolymeren," Acustica 21, 189-198 (1969).

Summary: Two-circuit resonance systems which contain a thin layer of an elastic material of high relaxational losses permit absorption of waterborne sound over a wide range of frequencies. The

properties of such absorbers are studied in detail. Relations which exist between absorption and elastic properties of the material of the layer are examined. The necessary high mechanical losses in the elastomers restrict absorption to a very small range of temperature.

Note: This study brings out one of the disadvantages of the lossy solid in comparison with the lossy liquid when used in an absorbing system; the solid is restricted to a rather small range of temperature, whereas, the liquid has a much wider range.

54. K. Brendel and H.-W. Leuschner, "Wasserschall-Resonanzabsorber mit Reibungsverlusten in Flüssigkeitsschichten," Acustica 21, 260-262 (1969).

Summary: Mechanical loss factors of almost unlimited magnitude can be obtained with fluid damped one-circuit resonant systems. Thus extremely broadband absorption becomes possible. The realization of such absorbers, however, encounters considerable technological difficulties. Fluid damped two-circuit resonant systems require much less technological effort and display excellent absorption properties over a wide range of frequency and temperature.

55. J. G. Savins, "Non-Newtonian Flow Through Porous Media," Ind. Eng. Chem. 61, 18-47 (1969).

Note: This is a survey article with 185 references.

56. J. L. Lastinger, "Acoustic Characteristics of Woods at High Hydrostatic Pressure," J. Acoust. Soc. Amer. 47, 285-289 (1970).

Abstract: The acoustic absorption and speed of sound in various kinds of water-saturated wood at three grain orientations have been measured in the frequency range 3-8 kHz at hydrostatic pressure to 10 000 psi. The measurements were made in a 6-ft-long 2-in.-i.d. acoustic-impedance pulse tube. Absorption is greatest for sound propagated parallel with or at 45° to the grain of the wood, and least for perpendicular propagation; the sound speed is greatest parallel with the grain and least at 90°. Generally, the measured change in acoustic characteristics with hydrostatic pressure is negligible.

Classified Literature

57. L. A. Hannum, "Radiation Reducing and Anechoic Coatings," JUA(USN) 11, 531-546 (1961). (Confidential article)

58. F. R. Lewis, "Hull Coatings," JUA(USN) 15, 453-464 (1965). (Confidential article)

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Naval Research Laboratory Underwater Sound Reference Division P. O. Box 8337, Orlando, Florida 32806	UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

UNDERWATER SOUND ABSORBERS: A REVIEW OF PUBLISHED RESEARCH WITH AN ANNOTATED BIBLIOGRAPHY

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

James L. Lastinger and Gerald A. Sabin

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
August 5, 1970	ii + 36	58

8a. CONTRACT OR GRANT NO	9a. ORIGINATOR'S REPORT NUMBER(S)
NRL Problem S02-30 b. PROJECT NO RF 05-111-401-4471 c. d.	NRL Memorandum Report 2146 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Director (Code 8200), Naval Research Laboratory, P. O. Box 8337, Orlando, Florida 32806.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Department of the Navy (Office of Naval Research) Washington, D. C. 20360

13. ABSTRACT

The theoretical behavior of acoustic media is reviewed briefly to obtain an insight into the nature of the absorption problem and the limitations imposed by the theory. Then, the status of resonant and broadband absorbers and the methods used to evaluate them are examined. In conclusion, several areas needing further investigation are specified. It is pointed out that the need for absorbers within a tank would be reduced significantly--perhaps eliminated--if the acoustic impedance of the tank wall could be made approximately equal to that of water. An annotated bibliography is included.

DD FORM 1473 (PAGE 1)

S/N 0102-014-6600

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Acoustic media						
Theory						
Absorption						
Evaluation						
Anechoic tanks						
Underwater sound absorbers						
Acoustic impedance						
Bibliographies						

UNITED STATES GOVERNMENT

Memorandum

7100-123

DATE: 21 November 2003

REPLY TO ATTN OF: Burton G. Hurdle (Code 7103)

SUBJECT: REVIEW OF REF (A) FOR DECLASSIFICATION

TO: Code 1221.1

REF: (a) "Underwater Sound Absorbers: A Review of Published Research with an Annotated Bibliography" (U), J.L. Lastinger and GA. Sabin, Underwater Sound Reference Division, NRL Memo Report 2146, August 5, 1970 (C)

1. Reference (a) is an investigation of the theoretical limits of the acoustic absorbtion by various materials. Also, the method of evaluating the materials used for the types of radiation examined. Further study was recommended.

2. The technology and equipment of reference (a) have long been superseded. The current value of these papers is historical.

3. Based on the above, it is recommended that reference (a) be declassified and released with no restrictions.

Burton G. Hurdle

BURTON G. HURDLE
NRL Code 7103

CONCUR: Edward R. Franchi 11/24/2003

E.R. Franchi Date
Superintendent, Acoustics Division

CONCUR: Tina Smallwood 11/26/03

Tina Smallwood Date
NRL Code 1221.1